DexController : Designing a VR Controller with Grasp-Recognition for Enriching Natural Game Experience

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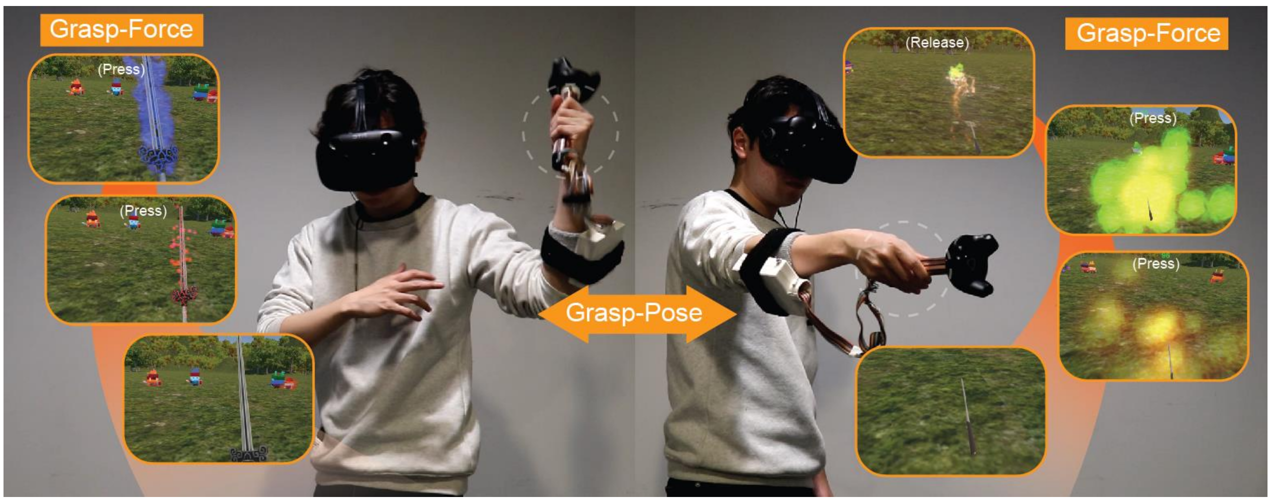

Figure 1: DexController recognizes user's grasp-poses for changing weapons in a VR game. Power grip activates a sword, and user's grasp-force intensifies the sword's strength with fire (Left). Precision grip activates a wand, and the grasp-force charges an attack magic while pressing and shoot it by releasing (Right).

ABSTRACT

We present DexController, which is a hand-held controller leveraging grasp as an additional modality for virtual reality (VR) game. The pressure-sensitive surface of DexController was designed to recognize two different grasp-poses (i.e. precision grip and power grip) and detect grasp-force. Based on the results of two feasibility tests, a VR defense game was designed in which players could attack each enemy using the proper weapon with a proper level of force. A within-subject comparative study is conducted with a button-based controller which has the same physical form of DexController. The results indicated that DexController enhanced the perceived naturalness of the controller and game enjoyment, with having acceptable physical demand. This study clarifies the empirical effect of utilizing grasp-recognition on VR game controller to enhance interactivity. Also, we provide insight for the integration of VR game elements with the grasping modality of a controller.

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CCS CONCEPTS

• Human-centered computing~Virtual reality • Human-centered computing~Empirical studies in HCI

KEYWORDS

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1 Introduction

Streuer [1992] insisted that presence the sense of being in an environment is the key factor of virtual reality (VR) experience. The dimensions that affect presence are largely divided into vividness and interactivity. Vividness is related to the type and performance of the display. Interactivity is deeply related to the VR controller's input method and the connection to the software, and it consists of elements of speed, range, and mapping. Among the elements, Seibert [2017] emphasized the importance of natural mapping for controllers which means that the input should be predictable given in-game happenings.

There have been many attempts to enhance the interactivity of VR games by adding various modalities as input methods. Amir et al. developed a first-person shooter (FPS) game using full-body interaction to enhance presence [Hezri et al., 2016]. BreathVR [Sra et al., 2018] used breath as a direct input method in a game to enhance the immersion of single and multi-player games. Onmyouji [Chou et al., 2018] explored VR experience with gesture-based game controls like moving and casting attacks. Beyond developing sensing technologies, these studies attempted to recognize the body's movement, map it naturally to a specific function in the game and observe its empirical effects on game experience.

Among technologies for controller, grasp sensing has gained increasing attention within VR field, with devices like the optical device [Potter et al., 2013], glove [Hinchet et al., 2018], and exo-skeleton [Choi and Follmer, 2016; Choi et al., 2018]. These studies have focused on accurately recognizing the finger positions and providing haptic feedback, which make the user feels like directly holding the virtual objects. In grasping, not only physical information transmitted from an object but also information such as a user's purpose or intention toward an objects are included [Wimmer, 2011]. In the human computer interaction (HCI) field, researchers have already studied methods of sensing and utilizing information streams during the grasping process. These methods can be used to understand the user's intention through gathering data of the user's hand. It can be used to actively reflect on the interface [Goel et al., 2012, Kim et al., 2016; Negulescu and McGrenere, 2015; Song et al., 2011] and to design more natural interactions with real-world analogs [Taylor and Bove, 2009]. In this way, grasping contains meaningful information, and sensing it can be an applicable way to increase interactivity in a VR game. However, even though many of related sensing technologies has been developed, there are insufficient empirical research about the mapping between grasping data and the design factors of VR games.

Our research aimed to explore the possibility of leveraging grasp-modality as VR game interface. We progressed this study in three steps as Figure 2. We set two variables based on the grasping modality (grasp-pose and force) and developed DexController to detect them sufficiently. Two feasibility tests were conducted to confirm the DexController's performance (N = 10). Then, a VR defense game was designed in which players can change the in-game weapon with grasp-pose and control power of attack with grasp-force. Through a comparative study (N = 12) with a button based controller, we investigated the empirical effects of grasp modality on VR game experiences. DexController shown significantly higher perceived naturalness and game enjoyment with increased physical demand.

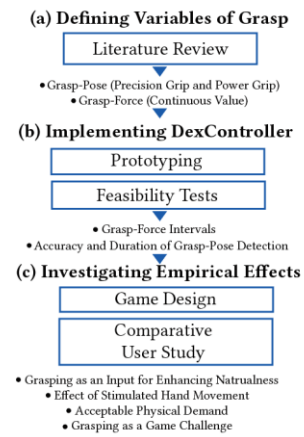

Figure 2: Pipeline of this study. Through the literature review, we defined two variables of grasping modality (a). DexController was designed to detect them enough and the feasibility tests were conducted. The results determined practical intervals of grasp-force and confirmed accuracy and duration of grasp-pose detection (b). A VR defense game was designed based on them and the user study was conducted (c).

We discussed the role of grasp-recognition regarding how it could mediate real and virtual environments naturally and how it engaged participants to play in immersive and extensive ways. The insights for integration of VR game elements with grasp-modality (i.e. grasp-force and grasp-pose) seem to be helpful for VR game developers who wants to design an immersive game with grasp-sensing controller.

2 Related Works

In this section, we review the literatures related to the natural interactions in VR games and the use of grasp-recognition in HCI fields.

2.1 Natural Mapping of Game Interaction

Mapping is "an ability to translate into actions that make sense to the user" [Steuer, 1992]. Seibert [2017] emphasized the influence of how control types naturally mapped on a game interface. It is defined as "natural" according to how closely represented the user's action are in in-game happenings. At the same time, it is affected by the technical aspects and cognitive differences such as the individual's mental model [Tamborini and Bowman, 2010]. When the game's input method and in-game happening are naturally mapped, the user becomes more immersed in the virtual environment and enjoys the game [Wirth et al., 2007]. In other words, a controller with high user-perceived naturalness leads to high presence and game enjoyment.

As Biocca [1992] and Norman [2002] have argued about natural mapping, the previous studies have confirmed that designing game input using real-world analogies can enhance presence. McGloin et al. [2011] compared the game experience with a gamepad to that with a motion capture controller while playing a tennis game. They found that the swinging motion of the motion capture controller was natural because of its similarity to real-world analogy of playing tennis. On the other hand, Limperos et al. [2011] found that the user felt PS 2 controller more natural than the Wii controller while playing the American football game. Rogers et al. [2015] confirmed a similar result that it is natural to use a familiar game interface rather than assigning a real world analogy to the contents with the player's unclear mental model. For example, a player who do not have driving license would feel more natural to play car driving game with a gamepad rather than a steering wheel. Thus, figuring out which game components can be naturally mapped with an additional modality is important while designing a new input method.

2.2 Leveraging Grasp-Recognition

Grasp is one of the most frequent and common human behaviors that people naturally reveal while using hand tools and manipulating objects in the real world. The Graspables [Taylor and Bove, 2009] suggested that grasp recognition can be a more natural method of interacting with devices. The study provided a new way of manipulating objects in a virtual environment with real-world analogs (e.g. grabbing, rubbing, and squeezing). The process of grasping an object is a bi-directional transfer that not only sends the object's information (objects, shapes) to hand but also carries the information pointing to the object in the hand [Wimmer, 2011].

Grasp-recognition is an active information gathering process regarding a user's intention and the usage context. Studies have leveraged gathered data of grasp through various techniques for proper contexts in the HCI field. Negulescu and McGrenere [2015] ised grip change as a source of information for mobile interaction. They built a side channel of mobile device to keep detecting the user's grip, and the interface actively adapts its appearance to the position of the user's thumb. Yoon et al. [2015] combined grip sensing with the device movement for active reading with a tablet. For the application of a stylus pen, the Multi-Touch Pen [2011] showed the possibilities to utilize grasp sensing and touch gestures for flexibility in use. Such studies have tried to overcome the limitations of fixed hardware, such as comfort problems. Sharma et al. [2019] suggested an organized set of micro-gestures that could be used in a tool-holding situation through an elicitation method with real users.

In the VR field, a variety of devices have been developed to reflect the status of the user's hands onto the virtual environment. Glove and exo-skeleton controllers have been developed to recognize more exact finger's position and strength, and mainly focused on giving the impression of actually touching objects through the haptic feedback [Choi and Follmer, 2016; Choi et al., 2018; Hinchet et al., 2018]. In recent years, the Valve corporation's Knuckles controller is underway to recognize the finger's location and pressure while grasping the motion controller [Valve Corporation, 2018]. The Leap Motion [Potter et al., 2013] has enabled various bare hand interactions, which has enabled a variety of gestural interactions. Amir et al. [2016] developed a VR FPS game with full body interaction to enhance interactivity using the Leap Motion and the Kinect. They mapped the navigation function to leg movement data from the Kinect and menu functions to gestural data from the Leap Motion. Chou et al. [Chou et al., 2018] developed a game that the character's movement and casting attacks responds to the hand's gesture for higher naturalness and immersion. These studies did not take quantitative measurements, but they tried to recognize the hand's data and use it as an integrated VR game interface.

As such, there have been studies to accurately convey physical information of the hands in virtual environment, and to create an intuitive game interface and natural interaction based on this information. However, like other areas of HCI, it is still necessary to suggest specific implications with grasp-recognition mapped to the actual function of the VR game interface or to understand its empirical effect.

3 DexController Design

We designed DexController in the following three steps. At first, we defined two input variables that can represent the grasping modality. Then, we designed the controller's components to sufficiently detect those input variables to implement in a VR game. Finally, we designed a VR defense game in which user should utilize proper variables and levels of grasping to accomplish game tasks.

3.1 Grasp Design

In this paper, we decided to follow the definition of grasp of "firm hold or grip" [Wimmer, 2011]. We set two variables: grasp-pose and grasp-force. Grasp-pose means where the fingers are positioned on the controller's surface, and grasp-force is the sum of the pressure from the whole surface.

Unlike contexts of using mobile devices [Negulescu and McGrenere, 2015; Song et al., 2011], the functions of games are not typically classified, so it is hard to set up typical functions and design the grasp modality. Therefore, we wanted to make the grasp variables as simple as possible and examine the empirical effects of each variable. Many previous research studies have focused on building a classification of grasps [Feix et al., 2008; MacKenzie and Iberall, 1994; Napier, 2005]. We chose two typical grasp-poses (power grip and precision grip) from Napier's classification model [2005]. Power grip involves the palm contacting a tool's surface, while the precision grip does not (see Figure 4 (a) and (b)). DexController can identify whether the grasping is power grip or a precision grip, and also detect the grasping force.

3.2 Hardware Design

DexController is designed to recognize two different grasp-poses and a range of grasp-force. To reduce any unintended effects of form factor, we designed the controller in a cylindrical shape which is a universal shape for various hand tools (e.g., pen, wand, broomstick and bat). The acryl cylinder's diameter is 27mm and length is 175mm. The weight of VIVE tracker and the body of DexController was approximately 160g (excepting the wire and the case). Wires of pressure sensor go through inside of the cylinder.

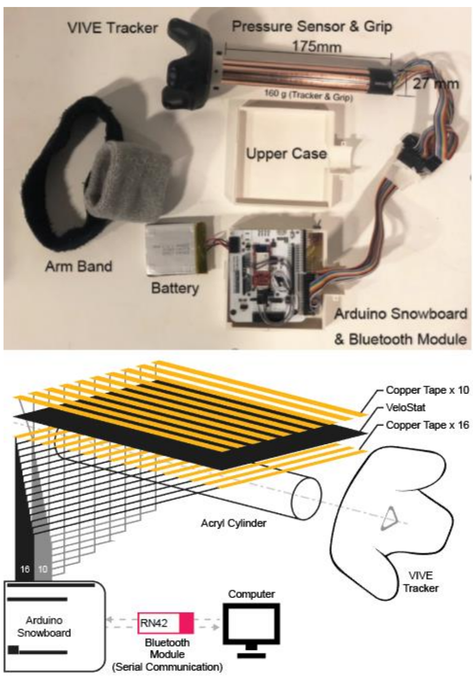

Figure 3: Hardware configuration of DexController

Typically, there have been two ways to capture human grasps. Instrumenting the users' hand through optical sensors is good to recognize hand pose precisely. The other way, grasp sensible surfaces with capacitive sensors [Sato et al., 2012; Song et al., 2011], acoustic waves [Funato and Takemura, 2017; Ono et al., 2013], and pressure sensors [Moeller, N.A.] recognize hand indirectly through the contact area. Because the previous way cannot detect grasp-force, we decided to use a pressure sensor for detecting pressure and position of contacting area. It consisted of 16 × 10 copper tape lines and velostat layer (Figure 3). The sensor layer was surrounded on the body of acryl cylinder. The Arduino Snowboard detected the change of resistor between the copper tapes and calculated the pressure data matrix. For a passage of wires, there was a 4mm vertical blind region that cannot detect pressure. All the circuits were cased in 3D printed box (104mm x 100mm x 36 mm) and user worn it on arm. Top part of the controller was joint with the VIVE tracker. The Arduino Snowboard circuit was powered by lithium polymer battery with 7.4V. It consisted of the pressure sensor and RN-42 Bluetooth module for serial communication.

3.3 Software Design

The classification of two grasp-poses was based on the difference of contact area between power grip and precision grip. Because of the cylindrical shape, people could hold it with different orientations while intending same grasp-poses. We needed to extract features that are independent of users' various hand orientations [Song et al., 2011].

We used connected component analysis [Bouman, 2014] to track the pressure clusters for each frame of data in real time. It was the simplest algorithm to recognize segmentations from a digital image; in this case, the pressure map. A total of 160 points of pressure information were input as byte format, and they were arranged in a matrix of 16 × 10. If the data of two adjacent cells exceeded the threshold (15 in raw value), it was clustered. We utilized the number and size of the clusters to classify the user's grasp.

To recognize precision grip and power grip, we set the threshold of cluster area. The controller detected precision grip if a number of clusters exceeded two and all the clusters' sizes were smaller than the threshold. Contrary to the precision grip, if there was only one cluster or one of the clusters was oversized, the controller detected power grip. The other cases were detected as default. We built a test program on the Processing 3.3.5 (Figure 4 (c) and (d)).

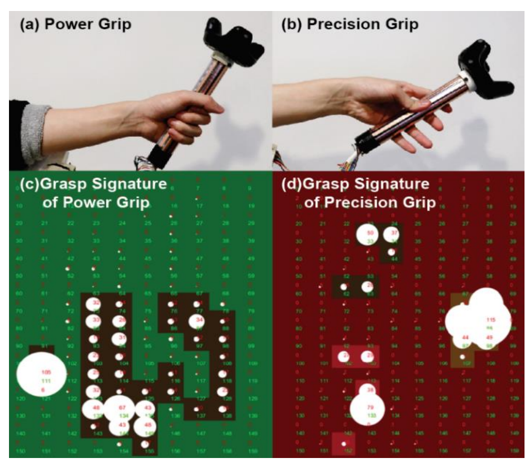

Figure 4: Two types of grasp-poses and the grasp-signatures. The different colors of the blocks represent different clusters. Each size of white circles represents the pressure of each point.

3.4 Grasp-Force Interval Determination

The grasp-force is a continuous value, but it should be able to convert into interval data. To check how many levels of interval could be recognized by a player, we conducted a short experiment to determine the pressure intervals of the two types of grip (power and precision grips).

Ten subjects (six males; mean age: 26.8 y) have participated. They were asked to grasp DexController with both grips and change the grasping pressure with seven levels. The first level was for their weakest pressure with the grips, and the seventh level was for the strongest pressure they could exert. The gap of the levels was left to their own judgment. Each subject was asked to exert the grasping pressure for each level. When he/she kept it stable, he/she pressed a record-start button ('A' button of a keyboard), then 15 pressure sensor values(sum of 160 points' values) of DexController were collected for a 750 ms (20 Hz). At the same time, state value which represents grasp-pose (0 : None, 1 : Power Grip, 2 : Precision Grip) is classified from the pressure data. From the first level to the seventh level, they repeated each level seven times (total 49 trials for each subject); as a result, total 7,350 (49 × 15 ×10) pressure values and state values were collected for each grip.

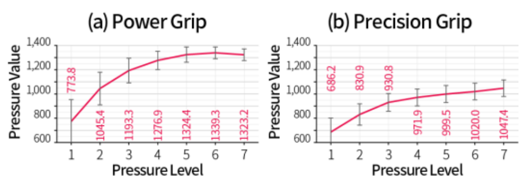

Figure 5: Pressure sensor mean values of DexController by pressure level. Red numbers in garaphs are the mean values.

Table 1: Correctness rates (percentage) of target grips by the grasp classification process.

Level	1	2	3	4	5	6	7	Total
Power Grip	60.8	85.0	86.3	96.4	94.1	98.8	97.1	88.3
Precision Grip	53.5	84.6	86.4	89.5	86.9	87.1	90.2	82.6

Figure 5 shows the pressure sensor mean values by the seven pressure levels, and the graphs converge as the level increases. It means that DexController cannot distinguish the grasping pressure above a certain level. The pressure values of the fifth level to the seventh level of the power grip were not significantly different (repeated measures ANOVA post-hoc). The mean values for the precision grip had significant differences (repeated measures ANOVA post-hoc; $p < .05$); however, the difference between the values of the fifth level and the seventh level was negligible (approximately 47.9). Meanwhile, we examined whether the participants' grips matched the target grip with our classification method during the experiment, and Table 1 shows the correctness rates by the pressure level. The correctness rates of the first levels were 60.8% and 53.5%, which was remarkably lower. It means that a minimum pressure level (at least, the second level) is required for normal operation of the classification method. From the results, we accepted the mean pressure values from the second to the fifth levels as a criterion for discriminating the grasping pressure.

4 Feasibility Tests

To examine that the grasp classification method and the grasp-force discrimination method of DexController, two feasibility tests were conducted. Twelve right-handed subjects (five females; mean age: 25.7) were recruited, and they participated in both tests.

4.1 Grasp-Pose Recognition Test

At first, we wanted to verify how fast and accurately DexController recognized both grips. The participants were asked to hold DexController left on the desk with one of the grips (target grip). When the pressure sensor value exceeded 350 (when holding DexController), recording of the trial time started (t_0). If the classification method determined their grip was the power grip, the state became 0 to 1. In the case of the precision grip, the state became 2. If the state was consistent with the target grip state and it maintained for 5 seconds, the trial was a success (t_s). If the trial time exceeded 15 seconds, the trial failed. When the participants' grips were confusing, the state changed back and forth from 0 to 2. Fifteen trials were assigned to each grip, so each subject performed total thirty trials.

Table 2: Mean task completion times and correctness rates

	Task Completion Time	Correctness Rate
Power Grip	1.59 sec. (SD: 0.72)	92.2 %
Precision Grip	1.69 sec. (SD: 1.01)	94.4 %
Total	1.64 sec. (SD: 0.88)	93.1 %

4.1.1 Result . The task completion time for each trial (t_c) was calculated as 't_s (the time when the trial succeeded) − t_0 (the first time when DexController was held) − 5 seconds (success determination time)'. The mean task completion times for the power and the precision grips were 1.59 seconds (SD: 0.72) and 1.69 seconds (SD: 1.01), respectively. There was no significant difference between the task completion times for both grips (independent samples t-test; $t(303) = -1.14$, $p = .25$). The correctness rates for the power and the precision grips were 92.2% and 94.4%, respectively. Comparing the correctness rates of Table 1 and Table 2, it also supported that the classification method was much improved since we added an average filter to stabilize the raw data.

4.2 Grasp-Force Recognition Test

The purpose of this test was to confirm that the participants were able to control and maintain the pressure input of the four levels. The participants were provided DexController and a LCD monitor, which displayed a white cube, changing with the pressure value of DexController; thus, the cube became larger when the participants held DexController harder. When the test started, a translucent red cube (start-pressure cube) appeared overlaid on the white cube. At this time, the participants were asked to adjust the size of the white cube to the size of the red cube by controlling their grasping pressure. After maintaining the size for three seconds (size tolerance: ±5%), a translucent green cube (end-pressure cube) appeared (t_0). They should adjust the size of the white cube to the size of the green cube and maintain it for five seconds (size tolerance: ±5%) in order to complete a trial (t_s). If the trial was not performed successfully for 10 seconds after the green box had appeared, the trial failed. The task completion time for each trial was 't_s (the time when the trial succeeded) − t_0 (the time when the green cube appeared) − 5 seconds (success determination time)'. Randomly 36 trials were given to each subject for one grip. Half of the participants performed the trials of the power grip first, and the other half performed the trials of the precision grip first.

Table 3: Mean task completion times and correctness rates

	Task Completion Time	Correctness Rate
Power Grip	2.08 sec. (SD: 1.03)	94.0 %
Precision Grip	1.61 sec. (SD: 1.03)	96.6 %
Total	1.84 sec. (SD: 1.05)	95.5 %

4.2.1 Result . Table 3 shows the mean task completion times and the correctness rates of the test. For the power grip, the participants could completed the tasks in an average of 2.08 seconds, and their correctness rate was 94.0%. On the other hand, the mean task completion time and the correctness rate for the precision grip were 1.61 seconds and 96.6%, respectively. The task completion times of both grips were significantly different (independent samples t-test; $t(822) = 6.65$, $p < .05$), which the participants performed the pressure control of the precision grip approximately 0.4 seconds faster than that of the power grip.

5 Game Design

Based on the results of the feasibility tests, we designed a VR defense game. We chose the defense game format which is one of the popular genre. The game environment consists of the HTC VIVE and Unity 2018.3.0f2. While designing the game elements, we focused on the following three setups. First, they should change weapons as the class of enemies is changing. Second, we designed the frequency never exceed the result of the feasibility test. Finally, grasp-force was mapped to the strength of the attack. A player can hold the level3 weapon to eliminate all levels of enemies, but it was expected to cause physical fatigue.

5.1 Weapon Design (Input Mapping)

While designing the weapons in defense game, we were inspired from the Swordplay [Katzourin et al., 2006]. They used gestures into weapon changing to implement an immersive defense game. We designed two weapons, a sword and a wand which are popular weapon type in fantasy genre games. Grasp-pose decided types of the weapon. Each power and precision grips were mapped to sword and wand. The weapons were chosen based on having real-world analogy of objects with each power grip and precision grip.

Grasp-force was used to control the power of weapons. Each weapon became stronger when a user grasped the controller more tightly. Although grasp-force was detected as a continuous value, we decided to convert it into interval data because the pressure value changed so fast and wanted to map it with the concept of 'level' in the game. Weapons had a gauge with three intervals that rose quickly in proportion to grasp-force, and also it could not exceed to next interval if the force was not enough (Figure 6). We decided to use the lowest pressure mean as a threshold for activating weapon switch. The other three pressure intervals from the previous tests were used as criteria of level intervals. Figure 1 (Right) shows that the sword was enchanted with fire while player grasped more tightly. In case of the wand, tight grasping charged magic on tip of the wand. When the player released the force, it shot magic to the direction of the tip. For both cases, the color of effects changed at the strongest state as Figure 1.

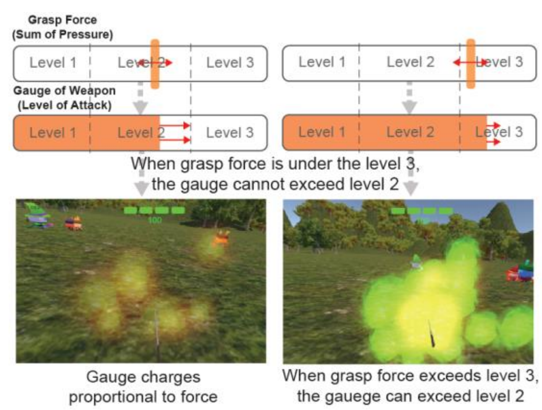

Figure 6: Diagram of how the grasp-force intensifies the weapon's level. For attacking at a higher-level, the grasp-force must exceed the level intervals.

5.2 Defense Game

Our defense game let players survive as long as possible by eliminating enemies. Three types of enemies were generated at 8m far from the player. They were randomly positioned in one of the player's 180 ° fronts. Each warrior, archer and wizards class attacked player in a different way. Warriors walked to the player until to be close enough to swing the sword. However, the player could not attack them with wand since they were immune to magic. On the other hand, wizards and archers stopped at a certain distance and shoot projectiles (magic and arrow). The player should use the wand to eliminate them.

Each class of enemies had 3 levels. Higher level enemy's attack was stronger than that of the lowers. Also, they were immune to players' lower level attack. If the player swung sword with level 1 gauge, it could not damage level 2 or 3 warriors. We designed sound feedback whether the attack worked or not. When the attack damaged to an enemy, hit sound and knockback animation played. On the other hand, if the attack failed, there was no knockback animation, and the different sound was played. If player use level 3 weapon, however, it could damage all levels of the enemy.

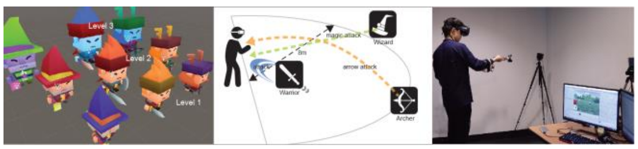

Figure 7: Three types of enemy characters has three levels(Left). The enemies randomly positioned in one of the player's 180 ° fronts(Middle). Experiment space setup (Right)

6 Comparative Study

6.1 Participant

Twelve subjects (five males; mean ages: 25.8 y) were recruited as participant for the comparative study. One participant was first time to use VR system, the others have a few experiences. Three of the participants were familiar with video console games.

6.2 Apparatus

The experiment space was 1.5m × 2.7m in a lab-space. Participants stood on a point and played game with fixed position. We used HTC Vive setup for participants to experience DexController and the VR defense game.

6.3 Experimental Design

We conducted a comparative study with a button-based controller and DexController. To exclude effects of form factor, we built the button-based controller like Figure 8. It had two buttons each mapped on the role of grasp-pose and grasp-force, and the other hardware parts were same with DexController. When the thumb button was pressed, the weapon was changed. The trigger button worked like grasp-force, but the strength rose in proportion to time. The duration is based on the result of grasp-force feasibility test.

The questionnaires consisted of the following items:

- Taskload : six items from NASA-Task Load Index (NASA TLX) survey [Hart, 2006]
- Immersion, Flow, Challenge, and Positive Effect : twelve items from the Game Experience Questionnaire [IJsselsteijn et al., 2013] core module
- Perceived Naturalness and Spatial Presence : each five items and three items from Rory et al. [MacGloin and Krcmar, 2011]

All the items were rated on the 1-7 Likert scale (1 : Not at all – 7 : A lot). After answering the questionnaires, we proceeded interview focused on the followings :

- Difficulties to use DexController
- Reason of perceived naturalness (if it was felt natural)
- The most impressive part of the game

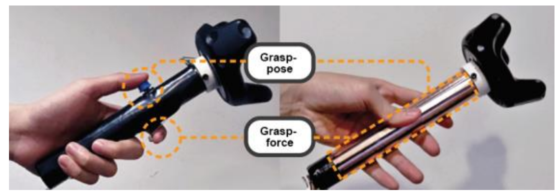

Figure 8: Inputs of the button-based controller. There are the thumb button switches weapons, and the trigger button charges the gauge.

6.4 Procedure

Each participant played the same defense game twice with different controllers in counter-balanced orders (the half played with DexController first, and the other half played with the button-type controller first). Each session consisted of 5 minutes practice time, 3 rounds of playing the game (each approximately 5 minutes), and questionnaire survey time. After the two sessions, a semi-structured interview of 10-15 minutes was conducted. Experiment of each participant took total 40 minutes.

6.5 Results

All the unweighted averaged scores of questionnaires were analyzed through pairwise t-tests (Bonfferoni pairwise comparison). Also, we scripted the records of the post-interview and classified the answers with the questionnaire's items; taskload, immersion, flow, challenge, positive effect, perceived naturalness and spatial presence.

6.5.1 Grasping as an Input for Enhancing Naturalness . The results of pairwise t-test (Figure 9) indicated that participants perceived DexController more naturally than the button based controller (Bonfferoni pairwise comparisons; ($t(11) = 5.89$; $p < .05$), and the spatial presence was also enhanced with DexController ($t(11) = 3.70$; $p < .05$).

The two controllers had significant differences in all the items of the GEQ, immersion (Bonferroni pairwise comparison; $t(11) = 2.44$; $p < .05$), flow ($t(11) = 2.24$; p = < .05), challenge ($t(11) = 3.63$; $p < .05$), and positive affect ($t(11) = 3.80$; $p < .05$). This means that the participants fully enjoyed the VR game with DexController. The result seemed to coincide with those of P.Skalski et al. [2011]: that the perceived naturalness of controller positively affects game enjoyment and spatial presence.

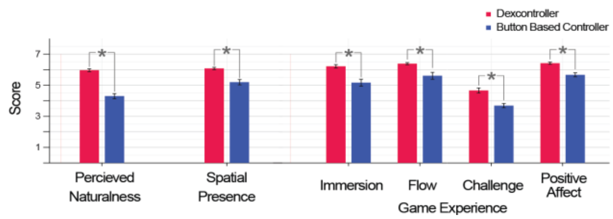

Figure 9: Results of Perceived Naturalness, Spatial Presence, and Game Experience Questionnaire. An asterisk (*) indicates significance at $p < 0.05$.

> "I was very familiar with the button action of the game device... However, relatively, I thought it would be more natural to give strength to my hands if I were a wizard or a swordman." – P11
> "In the real world, even if you cut something tough, it's better to give it more strength on the grip. I thought it was natural to give more force, where stronger power is needed." – P3
> "I think it's a great match for a simulation game where real hand positions and strengths are important, like tennis and baseball." – P4

As P11 mentioned, several participants stated that in both cases, it was natural and easy to memorize how to use and practice its usage VR gaming. Many participants answered that DexController's grasp-force recognition felt natural. As P3 said, in reality, it was natural that a tool would be firmly grasped for hard work, such as cutting tough things with a knife or chopping down a tree with an ax. Therefore, having to use stronger grasp-force on DexController to defeat stronger enemies was felt similar to the real-world analogy, and it led to the significant difference on the perceived naturalness.

6.5.2 Effect of Stimulated Hand Movement .

> "The second one (DexController) was more like using a real tool, while first one was felt like... kind of a mechanic." – P5
> "It would be more fun to shoot with a wrist snap. A wand ... if you wield something. I think it would be much more fun to combine with gestures." - P12

From the observation, participants' movement became more active when the game's situation was imminent while using DexController. We could observe a similar phenomenon for the button based controller, but DexController was showed to cause larger and more urgent movements. Some of the participants mentioned this in the interview. P2 said, "I was caring about my hand's pose and strength... When I was giving force with my hand, it affected my arm not only my hand.". Also, P12 wanted to use wrist snaps while using the wand during the experiment. The defense game in the experiment only used the hand aside from body movement, but participants expected some synergy or combination between grasping and body movement. Some participants pointed out that their whole body movement might be related to the enhanced spatial presence. As P5 said, DexController let users feel like using a wand or a sword in real so that they could be easily absorbed in the provided in-game situation. Having this feeling of spatially being in virtual environment, they could assume to be knights or wizards themselves. The resulted movement turned out in extensive and exaggerative ways, more than regulated grasping action in hands.

6.5.3 Acceptable Physical Demand . Regarding the NASA TLX survey, a pairwise t-test (Figure 10) indicated a significant difference in physical demand between DexController and the button based controller (Bonferroni pairwise comparisons; $t(11) = 2.58$; $p < .05$). Thus, the participants seemed to have physical difficulties in using DexController. However, the performance and frustration had no significant differences statistically, although DexController showed higher score.

> "Level 3, it's getting harder and harder to shoot... My hands are ache..." – P4
> "I thought the first (sword) would be much harder to use, but the second one (wand) was harder. I do not know why, but I was afraid to drop it."– P2 (while using DexController)

All of the participants answered that physical fatigue had occurred as they used more force than they did with button-based controllers. Five participants (P1, P2, P3, P4, and P7) stated that it was hard to press and release the precision grip (the wand in the game) with DexController. Notably, the precision grip seemed to make it easier to feel fatigued than the power grip (the sword in the game) did. During the experiment, some participants came close to dropping DexController early in the experiment.

> "The most impressive thing was that it was best to fight or to use 'power' in battle situations. I was really immersed in the power of the battle." – P10
> "It's conceptual, but it felt natural to focus and use energy to exert power."– P9

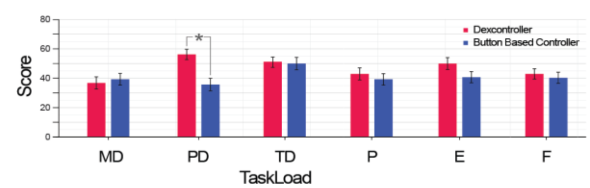

Figure 10: Results of that NASA TLX survey (MD : Mental Demand, PD : Physical Demand, TD : Temporal Demand, P : Performance, E : Effort, F : Frustration). An asterisk(*) indicates significance at $p < 0.05$.

Although the higher physical demand led to physical fatigue, it did not cause only negative effects on the game experience. In particular, the participants thought that the fatigue was a result of spending energy while devoting themselves to controlling a virtual environment. P7 said that giving power to the hand was a way to let the energy flow through the weapon, and accepted the fatigue as being natural. Also, P9 mentioned exhaustion after using the grasp-force felt more natural rather than pressing a button that has no cost for a stronger attack. For that reason, despite the physical burden and fatigue, there were no significant differences in performance, effort, or frustration; instead, DexController was accepted as a natural way for letting users to be immersed in virtual environment.

6.5.4 Grasping as a Game Challenge .

> "Pose affects the game a lot. I think it increased the game's difficulty." – P7
> "The button was much easier when I changed it then, but it feels a little bit like a thrill in hand. It will be more fun if you get used to it or if it is synchronized well." – P10

Our design of grasp recognition as a game input seemed to be perceived as a challenge to participants, resulting in a significant difference in quantitative evaluation of game experience. The participants replied that it was physically tiring to change their grasp-pose and to give force, but overcoming it also felt like a unique source of fun in the game. In the early stage of the experiment, the participants had experience some unwanted changes when using their in-game weapons, but the learning effect seemed to develop over time. As P10 mentioned, changing the weapon by pressing a button was similar to existing game interfaces and was not only familiar but also physically easier. However, the participants felt a sense of accomplishment when they succeeded in pulling out the weapon which they wanted through grasp-recognition. The grasp-force was mentioned as causing physical demand, as in the previous session. It caused physical fatigue, but it felt like using energy as a game component to the participants. The participants regarded the fatigue as a factor to overcome in playing the game.

7 Discussion

In this session, we will provide more in-depth discussions and future directions based on the results

7.1 Natural Mapping between Grasp and VR Game Components

We set the grasp-pose and the grasp-force as variables and then designed the VR defense game by mapping them to the different components. By comparing DexController and button-based controller through this game, we confirmed that the enhanced presence and game experience as the effect of natural mapping.

As Norman [2002] stated, the effect of natural mapping arises from the use of real-world analogy. Our findings indicated that using grasp-force strongly increased the perceived naturalness. In reality, firmly grasping a knife or a hammer is generally considered to mean making a stronger move or a physical collision. When a player expresses the concept of power (the strength of an attack or defense) with an existing general VR controller, it is replaced by a long press (with the feeling of charging magic or bullets). However, our utilization of grasp information afforded natural virtual experiences with real-world analogy by determining the in-game strength of the attack or defense with the hand's force.

Grasp-pose was paid less attention than grasp-force and was not as natural for the game design. Unlike with the using grasp-force, the participants seemed to lack a mental model of knife-holding or wand-holding poses, which were not familiar in real life. This seemed to be the same phenomenon as identified by Rogers et al. [2015], who argued that some game contents with weak mental models among players can be mapped more naturally with familiar interfaces like gamepads. Regarding future work, we expect a better naturalness as an effect of grasp recognizable controller, if we design a simulation game with a clear mental model related to the grasp-pose. As P4 mentioned, in some sports like golf or tennis, the grasp-pose could be a crucial factor for performance in the real world. While designing those kinds of sports-simulation games, grasp-pose can be a variable for the natural mapping with game components.

7.2 From Micro Grasp Recognition to Macro Bodily Movement

One of the interesting findings was that using DexController affected not only the players' hands but also their full-body movement. Participants using DexController showed more active movement as the game became more intense or immersive. While changing grasp-pose to change the weapon and adding force on the hand to defeat strong enemy, the sense of movements affected not only the hand but also the body. P12 wanted to continue to associate the precision grip with wrist snapping during the experiment. When the participants were changing their grasp-pose to change the in-game weapon, they seemed to find a more natural wrist angle or arm position which helps them to have whole presence in virtual world.

Yoo et al. [2018] suggested a model explaining the relationship between enjoyment and bodily exertion while playing VR games. According to the model, stimulating players to exert more than the player's recognition with multiple movements is better for game enjoyment. From the results of our study, using grasp as an additional modality for a VR game controller could enhance enjoyment of the VR game through stimulating body movement. In this study, we only focused on grasping of the hand, but the results showed the possibility of combining it with full-body interaction. When designers try to develop VR games using grasp modality, they should be aware of the possible effect of grasping on whole body movement and consider to utilize it as a game input strategy also.

7.3 Designing VR Game Challenge Using Intentional Physical Demand

This study found that the grasp-recognizing controller could provide challenge in VR game experiences. The unwanted change issues seemed problematic at an early stage of the experiment, but the participants learned their own strategy and proper grasp-poses, and they felt this as an achievement. Also, using grasp-force led to improved physical demand, but the participants felt it as a reasonable result of interaction (e.g. using power to strengthen weapon).

According to the model of immersion in mixed reality games [Hu et al., 2016], both physical and cognitive engagement lead to immersion. For our case of a VR game, we suppose that the grasp modality worked as a physical and real-world component in the immersion model. If we explain our result with the model, the process of memorizing the grasp-poses matching with the knife or wand worked as a mapping challenge. After building the mental map between grasp-poses and in game weapons, the increased physical demand afford player to make more physical effort which led to physical engagement. Our experiment considered simple grasp-poses, so it seemed that the mapping challenge caused less cognitive challenge (i.e., no significant differences on the mental demand). We expect that cognitive challenge can be provided by configuring a variety of grasp-poses and requiring specific grasp-force for VR game play. Game designers may utilize grasping as a design element for improved user engagement by affording cognitive and physical challenges from different grasping means.

8 Limitation & Futurework

This study's first purpose was exploring the possibility of grasping modality as VR game input, and we tried to figure out the empirical effects of each grasp-force and grasp-pose. If the study was designed to observe each variable on different games explicitly, it could be an ideal way to understand the empirical effects of leveraging grasp modality. However, utilizing a single variable of grasp modality was too simple to make participants experience enough in the game, and it was improper to our first goal. Further researches are needed for investigating each variable clearly. For example, we used grasp-force into three intervals, but it could be investigated deeper, whether five intervals or a continuous value is a better type of data for other contexts.

Our results had a necessarily limited scope in a case of VR game context. Also, the variables of grasp modality were designed to match to the existing function of a VR defense game, which can be a representative form of virtual gaming. In the midst of this, we had to make arbitrary decisions for consisting of familiar game format with the new input method, based on rationales from several empirical studies. However, as we discussed, some insights could be applied to other genre of games (e.g. sports or simulation game). In addition, we expect that grasping actions like squeezing or rubbing could be explored more as unique interactions (e.g., squeezing a cream in cooking game, spraying paint with grasp-force). Moreover, further researches can investigate the efficiency of leveraging grasp modality for more general spatial tasks. For example, grasp-force can be used as a gradual input unlike buttons, and grasp-pose can be used to select functions (e.g., precision grip activates the ray-cast). We cannot expect positive effects for general spatial tasks, because of the physical demand, which can be a positive effect on game experience (i.e., challenge). Nevertheless, it is still a worthy area to investigate.

9 Conclusion

In this study, we presented DexController leveraging grasp as an additional modality for enriching VR game experiences. The user study compared the use of DexController with the button-based controller in the context of a VR defense game. The results indicated that DexController induced higher perceived naturalness, spatial presence, and game enjoyment with the VR defense game. In addition, the stimulated hand movement led to full-body interaction, and an acceptable physical demand worked as a physical challenge. Our findings showed that utilizing meaningful information of grasping relates to real-world analogies and facilitates natural mapping with game contents. It could lead users to experience enhanced presence and enjoyment. Since both grasp-recognition and VR have gotten attention, this work can be especially beneficial for developers and game designers who want to improve the interactivity of hand-held devices and explore a new game design strategy for an immersive experience in VR.

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